The Economic Impact of Emissions Caps on Plug-in Hybrid Electric Vehicles

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ABSTRACT

This thesis explores the trade-off between cost and emissions of electric transport by limiting plug-in hybrid electric vehicles (PHEVs) to being no dirtier than conventional vehicles (CVs). We accomplish this by solving a unit commitment model of the Texas power system. The model was solved using a lagrangian relaxation technique and a sub-gradient algorithm. The results of the model show that PHEVs are a cost effective alternative to CVs regardless of emissions constraints. When the emissions restrictions are imposed PHEVs cost approximately $460 less per year per vehicle to drive than CVs, and approximately $3 more per year per vehicle to drive than when emissions restrictions are not imposed. Imposing emissions restrictions allows net CO_2, SO_2, and NO_x emissions to be significantly reduced for a small economic trade off. These reductions come from shifting coal generation to natural gas generation. These results are specific to the Texas power system and are highly influenced by the generation mix.

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NOMENCLATURE

PHEV	Plug-in Hybrid Electric Vehicle
CV	Conventional Vehicle
ERCOT	Electricity Reliability Council of Texas
MIP	Mixed Integer Program

1 Introduction

Plug-in hybrid electric vehicles (PHEV) have been touted as a cost effective, environmental transportation alternative to conventional vehicles (CV) with internal combustion engines. Although PHEVs have a higher up-front cost, primarily due to the battery, they can have lower operating costs which allow recovery of the battery premium over a number of years (1), (2). Furthermore numerous studies claim PHEVs have lower net emissions (*i.e.* including generator emissions related to battery charging) than CVs (1), (3), (4), (5), (6).

A study conducted in Texas suggests that the environmental impact of PHEVs is highly dependent on the generation mix of the system they are being used in (7). The analysis showed that PHEV use would result in a reduction in both vehicle and generator emissions of NO_x, but that CO_2 and SO_2 emissions could increase compared to CVs. This result hinged on the fact that close to one-third of PHEV recharging was done using coal-fired generation, whereas in other power systems more natural gas-fired generators are used (natural gas being a much cleaner source of energy than coal, especially in Texas where coal has higher than average sulfur content). Given the fact that studies of future PHEV use suggest coal may be the most cost-effective means of serving PHEV charging loads (3),(4), an important issue is to determine the economic cost and environmental benefits of using natural gas and other clean generation fuels for PHEV charging.

Our work broadens the existing research in (7) to further explore the trade-off between PHEV costs and environmental benefits. We use a similar mixed integer program (MIP) to minimize the costs of the generation mix used for PHEVs relative to environmental constraints to determine if PHEVs are a cost-effective means of reducing transportation emissions. These constraints were designed to require PHEVs to be no-dirtier environmentally than CVs.

In our analysis we found that PHEVs are economical to drive, even when not allowed to be dirtier environmentally that CVs. Under both scenarios the annual operating cost per vehicle of a PHEV under these constraints is approximately $460 less than the operating costs of a comparable CV, with the unconstrained scenario being slightly cheaper than the constrained scenario. The increased costs associated with the emissions constraint come from shifting coal generation to natural gas generation in order to meet the emissions constraints imposed.

2 Methods

Our analysis was completed using a unit commitment model of the Electricity Reliability Council of Texas (ERCOT) used in (7). The model optimizes generator commitment and dispatch decisions to minimize total generation costs while ensuring generators and vehicles are utilized within their constraints. The model is solved in two steps. The first is a unit commitment problem with a two-day planning horizon and coarse time step (4 hours) to determine the ending commitment and dispatch of each generator as well as the charge level of each PHEV battery. Afterwards a one-day problem with a finer, hourly, time step is solved to simulate dispatch and commitment decisions.

2.1 Model Data Sources

The unit commitment model is based off historical data in the ERCOT system from 2005. This section goes into detail on where this data comes from.

2.1.1 Power System Data

The generators included in this model consist of all thermal, hydroelectric, and wind generators operating in 2005. Generation costs are estimated based on heat rates, fuel and emissions permit prices, and operation and maintenance costs. They are modeled in three parts: startup costs, spinning no-load costs, and generating costs. Generators are modeled by typical constraints such as: load balance, reserve requirements, generation limits, ramping limits, and minimum/maximum on/off limits.

This data was obtained from Global Energy Decisions and Platts Energy. Wind availability data was taken from a mesoscale model by AWS Truewind for the National Renewable Energy Laboratory.

2.1.2 PHEV Data

We assume that PHEV batteries have a storage capacity of 9.4kWh. This corresponds to a PHEV capable of driving on its battery between 20 and 40 miles depending on vehicle class. Furthermore the batteries can only be discharged to 30% state of charge. Once PHEV batteries reach this minimum state of charge, they enter charge sustaining mode, where PHEVs drive primarily on gasoline rather than their battery. In charge depleting mode, PHEVs drive on their battery. PHEV costs modeled consist of gasoline and battery recharging costs. Gasoline costs are taken from historical weekly price reports for the state of Texas from the U.S. Department of Energy's Energy Information Administration and electricity costs are taken from the unit commitment model solved. PHEV driving and charging patterns are based on driving profiles that were determined using data from a survey conducted by the East-West Gateway Coordinating Council detailed in (8) and (9) with an additional assumption that PHEV batteries must be fully recharged by 4a.m. The case examined is 1% PHEV fleet of 60,000 vehicles split evenly between the driving profiles. The gasoline and battery usage for CVs and PHEVs was determined using the Advanced Vehicle Simulator described in (10).

2.1.3 Emissions Data

To estimate generator emissions, we use input-based emissions rates, which give emissions based on each unit of fuel burned. Estimating emissions this way allows for greater accuracy. These rates are assumed constant and derived from historical continuous emissions monitors data reported to the Environmental Protection Agency. This is covered in more detail in (7). The emissions data used to constrain the model are listed in table 1.

Type of Emission	No Vehicle Generator Emissions (Lbs)	CV Tailpipe Emissions (Lbs)	PHEV Tailpipe Emissions (Lbs)
CO_2	944,789,771,996	800,306,622	200,630,577
SO_2	2,202,961,600	14,905	3,736
NO_x	632,302,944	162,535	57,580

Table 1 - Annual Generator and Vehicle Emissions

All emissions are in pounds. No vehicle generator emissions are taken from a case with no PHEVs included in the model. PHEV and CV tailpipe emissions are taken from the Advanced Vehicle Simulator in (10).

2.2 Unit Commitment Model Formulation

This section contains a formulation of the unit commitment model used.

2.2.1 Sets

- T: All hours in unit commitment planning horizon
- G: Set of generators
- V: Set of PHEV types (driving profiles)

2.2.2 Parameters

- $C_g(q_{g,t})$: Stepped generation cost function of generator G
- NL_g: No-load cost of generator G
- SU_g: Startup cost of generator G
- ${t_g}^-, {t_g}^+$: Minimum down and up time of generator G, respectively
- ${R_g}^-, {R_g}^+$: Ramp down and up rate of generator G, respectively
- ${K_g}^-, {K_g}^+$: Minimum and maximum capacity of generator G, respectively
- NV_v: Number of PHEVs with driving profile V
- $\bar{p}$: Maximum power which can be drawn/put into PHEV battery (MW)
- e^-, e^+: Minimum and maximum SOC of PHEV battery, respectively
- ce, de: Charge and discharge efficiencies of PHEV battery, respectively
- $dist_{v,t}$: Total distance (miles) driven by profile V in hour T
- γ: Price of gasoline ($/gallon)
- D_t: System load in hour T
- p^s, p^t: Spinning and total reserve requirements (as a fraction of load), respectively
- ${cd^G}_v, {cs^G}_v$: Average gasoline usage of profile V in CD and CS modes, respectively
- ${cd^E}_v$: Average battery usage of profile v

2.2.3 Variables

- $q_{g,t}$: Generation provided by generator G in hour T
- $sp_{g,t}, ns_{g,t}$: Spinning and non-spinning capacity reserved from generator G in hour T
- $u_{g,t}, s_{g,t}, h_{g,t}$: Binary variable indicating if generator G is up, started-up, and shutdown in hour T, respectively
- $SOC_{v,t}$: State of charge (MWh) of each PHEV type V in hour T
- $ch_{v,t}$: MW of charge put into PHEV V in hour T
- ${cd^m}_{v,t},\ {cs^m}_{v,t}$: CD and CS miles driven by PHEV V in hour T, respectively
- $\widetilde{cd}_{v,t}$: Binary indicator for whether the PHEV V is in charge-depleting mode or not in hour T

2.2.4 Objective Function

$$minimize\ total\ cost:$$

$$\sum_{G,T} C_g\left(q_{g,t}\right) + NL_g u_{g,t} + SU_{g,t} s_{g,t}$$

2.2.5 Constraints

- Load Balance $\forall\, T$

$$\sum_{G} q_{g,t} + \sum_{V} \frac{NV_v ch_{v,t}}{ce} = D_t$$

- Total and Spinning Reserve Requirement $\forall\, T$

$$\sum_{G} sp_{g,t} \geq p^s \left(D_t + \sum_{V} \frac{NV_v ch_{v,t}}{ce} \right)$$

$$\sum_{G} \left(sp_{g,t} + ns_{g,t}\right) \geq p^t \left(D_t + \sum_{V} \frac{NV_v ch_{v,t}}{ce} \right)$$

- Generator Lower Bound ∀ G, T

$$K^{-}u_{g,t} \le q_{g,t}$$

$$q_{g,t} + sp_{g,t} \le K^{+}u_{g,t}$$

$$q_{g,t} + sp_{g,t} + ns_{g,t} \le K^{+}$$

- Ramp Down ∀ G, T

$$R_g{}^{-} \le q_{g,t} - q_{g,t-1}$$

- Ramp Up ∀ G, T

$$q_{g,t} - q_{g,t-1} + sp_{g,t} + ns_{g,t} \le R_g{}^{+}$$

- Minimum On and Off ∀ G, T

$$\sum_{\tau = T - t_G{}^{-}} su_{g,\tau} \le u_{g,\tau}$$

$$\sum_{\tau = T - t_G{}^{+}} h_{g,\tau} \le 1 - u_{g,\tau}$$

- Startup State Transition ∀ G, T

$$s_{g,t} \ge u_{g,t} - u_{g,t-1}$$

- Shutdown State Transition ∀ G, T

$$s_{g,t} \ge u_{g,t-1} - u_{g,t}$$

- PHEV battery State of Charge Balance ∀ V, T

$$SOC_{v,t} = SOC_{v,t-1} + ch_{v,t} - cd^{E}{}_{V} cd^{m}{}_{v,t}$$

- PHEV Driving Requirement ∀ V, T

$$cd^{m}{}_{v,t} + cs^{m}{}_{v,t} = dist_{v,t}$$

- PHEV Charge Depleting Mode Definition ∀ V, T

$$\widetilde{cd}_{v,t} \ge \frac{SOC_{v,t} - \mathrm{e}^{-}}{e^{+} - \mathrm{e}^{-}}$$

- PHEV CD to CS mode Transition $\forall\, V, T$

$$cs^{m}{}_{v,t} \leq dist_{v,t}(1 - \widetilde{cd}_{v,t})$$

- Integrality of PHEV variables $\forall\, G, V, T$

$$u_{G,T}, s_{G,T}, h_{G,T} \in \{0,1\}$$

$$\widetilde{cd}_{v,t} \in \{0,1\}$$

2.3 Emissions Constraints

Additional emissions constraints were added to the unit commitment model for our analysis. The constraints are used to limit PHEV emissions to being no-worse than CV emissions on an annual basis. The formulation for these constraints is covered in this section.

2.3.1 Additional Sets

- e: set of emission types (CO_2, SO_2, NO_x)

2.3.2 Additional Parameters

- $G^{E}{}_{g,e}$: average emission rate for each emission type at each generation
- $HR_g(q_{g,t})$: stepped heat rate function of generator G
- $SU^{H}{}_{g}$: average heat given off on startup for generator G
- $NL^{H}{}_{g}$: average heat given off by generator G
- $PHEV^{E}{}_{e}$: average emission rates of emission e given off by PHEVs
- $CV^{E}{}_{e}$: total annual emission e (generator and tailpipe) given off by CVs

2.3.3 Additional Constraints

$$G^E{}_{g,e}\sum_{G,T}\left(q_{g,t}HR_G\left(q_{g,t}\right)+u_{g,t}NL^H{}_g\ +s_{g,t}SU^H{}_g\right)$$
$$+\sum_{v,t}PHEV^E{}_e\left(cd^G{}_{v,t}cd^m{}_{v,t}+cs^G{}_{v,t}cs^m{}_{v,t}\right)\leq\ CV^E{}_e\qquad\forall\, e$$

The formulation of this constraint forces t to span all 8760 hours in the year in order for annual PHEV emissions to be no worse than annual CV emissions.

2.4 Solving the MIP

Due to the computational complexity of solving all 365 days simultaneously a lagrangian relaxation technique was used. This technique decouples the problem into 365 individual problems by removing the annual emissions constraints and placing them in the objective function (11). This is done by imposing a different penalty cost (λ_e) for each pound of NO_x, SO_2, and CO_2 emitted over the entire year. The modified objective function is:

$$minimize\ total\ cost:$$
$$\sum_{G,T}C_G\left(q_{G,T}\right)+NL_Gu_{G,T}+SU_{G,T}s_{G,T}+NV_V\sum_V\gamma\left(\sum_T cd^m{}_{V,T}\,cd^G{}_{V,T}+cs^m{}_{V,T}cs^G{}_{V,T}\right)$$
$$+\lambda_e\left(\sum_{g,t}G^E{}_{g,e}\sum_s\left(q_{G,T}HR_G\left(q_{G,T}\right)+u_{G,T}NL^H{}_g+s_{G,T}SU^H{}_g\right)\right.$$
$$\left.+\sum_{v,t}PHEV^E{}_e\left(cd^G{}_{V,T}cd^m{}_{V,T}+cs^G{}_{V,T}cs^m{}_{V,T}\right)\right)$$

Imposing the penalty costs (λ_e) the problem allows the problem to be solved on a daily basis. The constraint can then be enforced by holding the sum of daily PHEV emissions less than CV emissions. The constraint takes the form where t only spans the 24 hours of each daily unit commitment problem:

$$\sum_{365\ days} \left(G^{E}{}_{g,e} \sum_{G,T} \left(q_{g,t} HR_G\left(q_{g,t}\right) + u_{g,t} NL^{H}{}_{g} \ + s_{g,t} SU^{H}{}_{g}\right) + \sum_{v,t} PHEV^{E}{}_{e} \left(cd^{G}{}_{v,t} cd^{m}{}_{v,t} + cs^{G}{}_{v,t} cs^{m}{}_{v,t}\right)\right) \leq \ CV^{E}{}_{e} \quad \forall\ e$$

2.5 Sub gradient Algorithm

The penalty costs are decided upon by a sub-gradient algorithm. The sub-gradient algorithm iteratively adjusts the penalty costs based upon best upper and lower bounds to produce the best (or nearly the best) solution. The algorithm, described in greater detail in (11), is outlined below.

- Find Initial Upper Bound λ_i = 1
- Find Initial Lower Bound λ_i = 0
- Update λ_i based on best upper and lower bound
- Solve model with new λ_i
- Save best upper and lower bounds
- Repeat until termination criteria are met

2.5.1 Find Initial Upper Bound

In order to use the sub-gradient algorithm, an initial lower bound needs to be found first. This is accomplished by setting all of the penalty costs (λ_is) to an arbitrarily large value and solving the problem. For this problem 0.1 $/lb was used because the emissions were modeled in units of pounds. The initial upper bound will have the highest objective function value and the lowest amount of each type of emission.

2.5.2 Find Initial Lower Bound

Similarly to the initial upper bound, the initial lower bound is required to begin the sub-gradient algorithm. The initial lower bound is found by setting all of the penalty costs (λ_is) to 0. This simulates the unconstrained scenario where emissions are not considered. The initial lower bound will have the lowest objective function value and the highest amount of each type of emission.

2.5.3 Update λ_is based on best upper & lower bound

After the initial upper and lower bounds are determined the algorithm can begin. The algorithm finds new penalty costs (λ_is) based on the difference between the best upper and lower bounds. The best upper bound is defined as the highest objective function value that violate at least one emissions constraint. The best lower bound is defined as the lowest objective function value that does not violate any of the emissions constraints. For the first iteration the initial upper and lower bounds are used. The change in penalty costs will decrease as the algorithm nears the optimal solution. The process is outlined below.

- Determine gaps (δ_e) between constraint and current iteration solution

$$\delta_e = CVemr_e - \lambda_e \left(\sum_{g,t} GENemr_{G,e} \sum_{s} \left(q_{G,T} HR_G \left(q_{G,T} \right) + u_{G,T} NLHR_G + s_{G,T} SUHR_G \right) + \sum_{v,t} PHEVemr(e) \left(cd^G{}_{V,T} cd^m{}_{V,T} + cs^G{}_{V,T} cs^m{}_{V,T} \right) \right)$$

- Computer step size (Δ) based on the objective functions of the current iteration ($z_{current}$) and lower bound (z_{lb}). π is a constant that initially starts at 2, is halved each iteration when no improvement is made to the objective function.

$$\Delta = \frac{\pi(z_{lb} - z_{current})}{\sum {\delta_e}^2}$$

- Adjust penalty costs (λ_e) based on the step size and gaps previously calculated

$$\lambda_e = max(0, \lambda_e + \Delta\delta_e)$$

2.5.4 Solve model with new λis

The model needs to be resolved every time the penalty costs are updated.

2.5.5 Repeat until termination conditions are met

The algorithm will repeat until the termination criteria are met. The termination criteria used for this study are outlined in the next section.

2.6 Optimality Conditions

The termination criteria used for this study was based on the duality gap. The duality gap is defined as the difference between the best upper bound and the best lower bound as a percentage of the best upper bound. The algorithm continually updates each penalty cost (λ) until reaching an acceptable duality gap. Tables 2 through 4 show the bounds used, penalty costs associated with those bounds, the termination criteria, respectively. The duality gap is very small and thus the solution was deemed very near-optimal.

Bound	Upper Bound	Best Upper Bound	Best Lower Bound	Lower Bound
$C0_2$ Emissions (Billion Lbs)	303.3	429.1	429.1	431.0
$S0_2$ Emissions (Million Lbs)	126.3	991.1	991.1	999.1
$N0_x$ Emissions (Million Lbs)	170.5	281.2	280.8	285.3
Cost (Billion)	18.7	12.5	12.5	12.5
Objective (Billion)	49.0	14.9	14.9	12.5

Table 2 - Annual Upper and Lower Bounds

Table 2 contains all emissions from generators. Tailpipe emissions are not included.

Bound	$C0_2$ Emissions	$S0_2$ Emissions	$N0_x$ Emissions
Upper Bound	0.10000	0.10000	0.10000
Best Upper Bound	0.00523	0.09926	0.09986
Best Lower Bound	0.00526	0.09932	0.09990
Lower Bound	0.00000	0.00000	0.00000

Table 3 - Penalty Costs

All penalty costs are in $ per pound and rounded to 5 decimal places.

Termination Criteria	Objective Function Difference	% Difference
Duality Gap	$ 8.5 Million	0.06%
Gap to Lower Bound	$ 2,384.0 Million	16.0%

Table 4 - Termination Criteria

Percentages are as a percentage of the best lower bound. Only generation costs are included.

3 Results

The results from the unit commitment model indicate that PHEVs can be used to lower vehicle driving costs even when constrained to be no dirtier than CVs. When drivers are allowed to make their own PHEV charging decisions it leads to extra charging during peak hours. Table 5 summarizes the incremental increase/decrease from the use of a 1% PHEV fleet (60,000 PHEVs). When PHEV emissions are unconstrained, net CO_2 emissions increase by 1.6 billion lbs while net SO_2 and NO_x emissions decrease by 174.2 thousand lbs, and 1.7 million lbs, respectively. Each PHEV results in a decrease in driving cost of $460 annually compared to a CV. There is a minor decrease in this savings when emissions constraints are forced on PHEVs ($3 annual per PHEV).

Metric	Unconstrained	Constrained
$C0_2$ Emissions (Lbs)	1,667,118,877	-218,884,579
$S0_2$ Emissions (Lbs)	-174,264	-8,187,009
$N0_x$ Emissions (Lbs)	-1,689,089	-6,138,963
Cost	-$35,260,391	-$35,021,929
Cost / Driver	-$466	-$463

Table 5 - Driver-Controlled Charging Scenario Incremental Increases

All of the values listed in this table are normalized from a baseline scenario with no PHEVs. The emissions include all tailpipe emissions from CV's and PHEV's and the cost includes all gasoline, generation, and vehicle charging/driving costs.

3.1 Generation Mix

Generation mix is the most significant driver in the net CO_2, SO_2, and NO_x emissions as well as the cost of energy generation. Coal generation is inexpensive and has high emissions rates (especially in Texas due to the higher sulfur content of coal). Natural gas is a much cleaner fuel, but at a higher cost. In order to minimize costs while meeting an emissions constraint the model is balancing how much coal and natural gas generation is used to produce energy for the increased loads from PHEVs.

Type of Generation	Increase	% of Increased Load
Coal	+14.4 K	6.1%
NG	+220.7 K	93.9%
Total	+235.0 K	

Table 6 - Unconstrained Generation Mix

The increases in column two reflect the difference between the unconstrained case minus the baseline case without PHEVs. Column three reflects what percentage of the total increased loads (from the addition of PHEVs) each type of generation accounts for.

Table 6 shows the changes in generation mix (relative to the case with no PHEVs) in the unconstrained emissions case. Nearly all of the increased loads are handled by natural gas generation. This suggests PHEVs that are recharged with natural gas generation are more cost effective than CVs driving on gasoline. Table 7 shows the same metrics for the emissions-constrained case. The addition of the emissions constraints changes the generation mix used. 550% of the additional loads from PHEVs are handled by natural gas. This means that coal generation that was used when no PHEVs were in the system is no longer used, and additional natural gas generation replaces it. The shift from coal generation to natural gas generation allows for PHEV CO_2 emissions to be no worse than CV emissions at a slightly increased cost.

Type of Generation	Difference	% of Increased Load
Coal	-1.1 M	-452.2%
NG	+1.3 M	+552.2%
Total	+235.0 K	

Table 7 - Constrained Generation Mix

The increases in column two reflect the difference between the constrained case minus the baseline case without PHEVs. Column three reflects what percentage of the total increased loads (from the addition of PHEVs) each type of generation accounts for.

3.2 Trends in Emissions Reductions

Emissions reductions achieved from constraining PHEVs to be no dirtier than CVs are spread across the entire year. There is no practical significance to what time of year CO_2 and SO_2 emissions occur at, but there is significance to when NO_x emissions reductions occur. During ozone season (March 1st to October 31st) temperatures rise and the amount of sunlight increases. NO_x is a precursor for ground level ozone and has negative implications such as smog during ozone season. Figure 1 shows that NO_x reductions occur during both ozone season and non ozone season, and that approximately half of the NO_x reductions occur during ozone season.

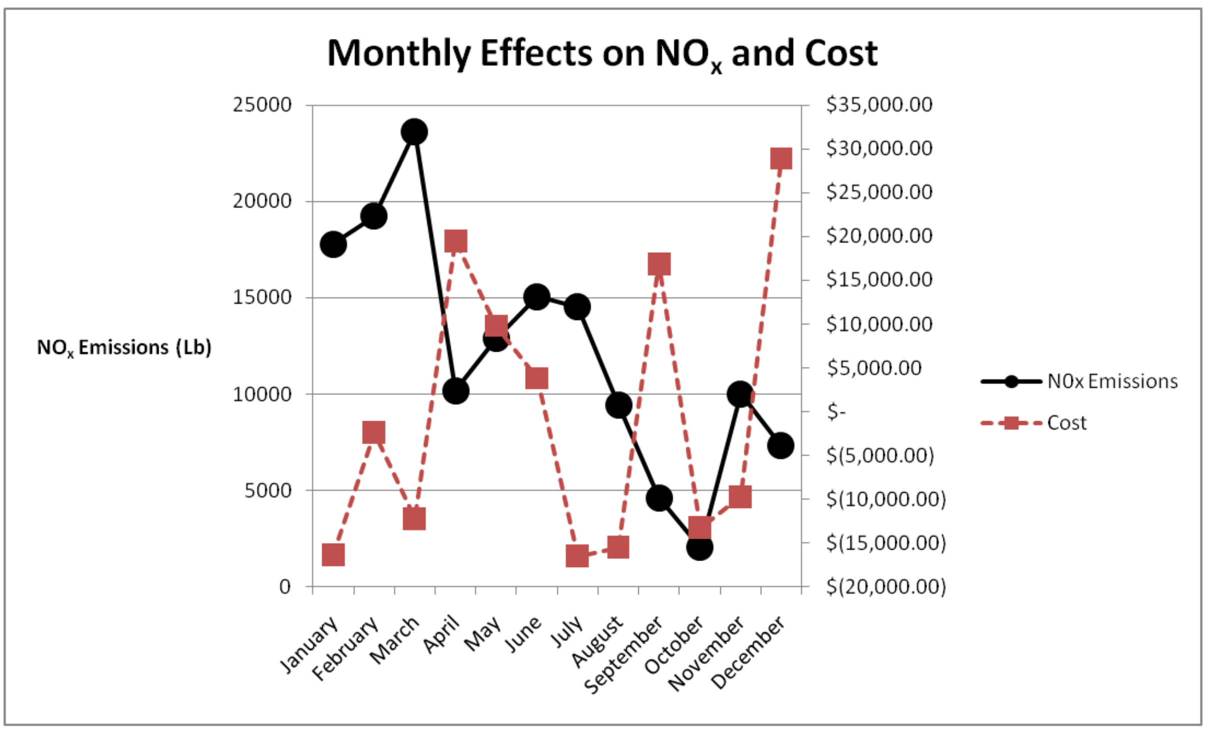

Figure 1 - Monthly Change in Generator NO_x Emissions and Cost

NO_x and cost numbers are average daily increases/decreases. Values reflect constrained scenario results subtracted from unconstrained scenario results. Figure 2 captures the effects of imposing emissions restrictions on PHEVs.

4 Conclusions

Based off our analysis, PHEVs are equally as economical when constrained to being no-worse than CVs in the system studied (ERCOT). The annual cost per vehicle decreases by $460 in both cases. The slightly increased costs come from the change in generation mix. When emissions are constrained coal generation decreases by 450% of the additional load added by PHEVs. Natural gas generation increases to account for the decrease in coal generation to meet demand. The change from coal generation to natural gas generation decreases the amount of generator emissions at a slightly higher cost. We conclude that imposing emissions caps on PHEVs (at 1% PHEV infiltration) to make them no worse environmentally than CVs has little effect on their driving costs.

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